

# Future Directions in Rotorcraft Technology at Ames Research Center

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## Abstract

Members of the NASA and Army rotorcraft research community at Ames Research Center have developed a vision for “Vertical Flight 2025”. This paper describes the development of that vision and the steps being taken to implement it. In an effort to realize the vision, consistent with both NASA and Army Aviation strategic plans, two specific technology development projects have been identified: one focused on a personal transportation system capable of vertical flight (the “Roto-Mobile”) and the other on small autonomous rotorcraft (which is inclusive of vehicles which range in grams of gross weight for “Micro-Rotorcraft” to thousands of kilograms for rotorcraft uninhabited aerial vehicles). The paper provides a status report on these projects as well as a summary of other revolutionary research thrusts being planned and executed at Ames Research Center.

## Introduction and Background

Through a synergy of Army Aeroflightdynamics Directorate and NASA Ames Research Center resources, the Army/NASA Rotorcraft Division (Ref.1) leads the Nation in both aeromechanics and flight control and cockpit integration technology development and insertion for military and civil helicopters, tiltrotor aircraft, and other advanced rotary-wing aircraft. The Division also provides the U.S. rotorcraft industry, Department of Defense, and other Government agencies with the technical expertise required to produce and field safe, affordable, and effective all-weather rotorcraft systems.

The strategic plan for the NASA AeroSpace Technology Enterprise (Ref. 2) is driven by a set of three “Pillar Goals” and ten “Technology Objectives”. Breakthroughs in rotorcraft and vertical flight technology can have significant

impacts on two of the Pillar Goals: “Global Civil Aviation” and “Revolutionary Technology Leaps”. “NASA must pursue high-risk research to provide needed technology advances for safer, cleaner, quieter, and more affordable air travel” (Ref. 3) in a future environment in which the demand for air travel is projected to triple in 20 years. NASA is committed to the Technology Objective of: “While maintaining safety, triple the aviation system throughput, in all weather conditions, within 10 years”. NASA’s AeroSpace Technology charter is also to explore high-risk, revolutionary technology areas that can result in a major expansion of personal mobility (“a seamless transportation system with tremendous doorstep-to-destination speeds” – Ref. 4) and provide significant increases in socio-economic opportunity, both in the U.S. and worldwide. This effort also includes providing for revolutionary new development tools for aerospace systems that will accelerate the application of technology advances.

The U.S. Army, in conjunction with the industry and the user community, has developed a top-down strategic planning approach (the Technology Development Approach, or TDA) and an associated Technology Area Plan (TAP) to guide the DoD

Science and Technology (S&T) efforts for rotary-wing vehicles. The strategic guidelines for this plan are: aggressively pursue S&T efforts aimed at high-payoff goals, establish common goals and technology transfer with industry, and emphasize affordability and dual-use technology (emphasis by the authors). As a result, although clearly focused on maintaining U.S. military capability and readiness, the attributes of the Army S&T Program show considerable commonality with the NASA AeroSpace Technology Enterprise goals.

The development of a strategic vision for the twenty-first century for integrated Army and NASA vertical flight research and technology represents both an appealing opportunity and a daunting challenge. The extremely productive, 35-year-old Agreement for Joint Participation in Aeronautical Technology between NASA and the Army Materiel Command has spawned many significant accomplishments in rotorcraft technology, including momentous advances in tiltrotor technology (focused on the joint development of the XV-15 tiltrotor research aircraft with Bell Helicopter – Ref. 5). This Joint Agreement offers the opportunity for further revolutionary breakthroughs. The challenge is, while maintaining a commitment to both NASA and Army research goals, to devise a “strategic implementation plan” consistent with the research goals of both organizations which provides both a vision and a roadmap to achieve that vision. Although it is important to define and adhere to a “process” to develop the strategic implementation plan, it is also important not to get lost in the process.

*Before the beginning of great brilliance, there  
must be Chaos.*

*Before a brilliant person begins something great,  
he must look foolish to the crowd.*

**The I Ching (“Book of Changes”, ca 1000 BC)**

Revolutionary developments in vertical flight technology, achievable under the auspices of the Joint NASA/Army Agreement, can solve critical national problems. Significant improvements in the U.S. transportation system can be achieved by safely alleviating airport congestion and delays in all weather conditions and by providing expanded access to the air transportation system. In addition, new and emerging defense needs --including counter-terrorism, urban warfare, and disaster relief -- require the development of highly-mobile forces

with efficient logistics delivery and a rapid growth in the application of Information Technology on the battlefield. Finally, advances in vertical flight technology can serve to meet the increasing demand for rapid-response public service operations such as emergency medical service, search and rescue, and law enforcement.

Given this challenge, this paper provides an overview of advanced research thrusts, describes the development of a vision for Future Directions in Vertical Flight Technology at Ames Research Center, and describes in more detail two focus areas specifically identified by the vision process for technology development.

### **Advanced Research Thrusts**

The Army/NASA Rotorcraft Division is engaged in a broad program of rotorcraft research and technology development. The elements of this program have the potential to advance helicopter and tiltrotor technology far beyond current levels. Within the aerospace spectrum, rotorcraft technology is relatively immature and therefore the future holds great potential if critical fundamental and advanced technology is aggressively pursued. Both the current immaturity and the future potential of rotorcraft technology stem from the same key factor - the fundamental complexity of rotorcraft aerophysics. In years past, the difficulties presented by these complex problems afforded only limited progress and incremental gains. Today, however, the situation is changing. New technologies, including composites, smart materials, and sensors will enable fundamentally new approaches to rotor design. With enormous new computer capabilities, we are on the threshold of solving scientific riddles of rotorcraft aerodynamics that have plagued technologists since the origin of the industry. And emerging information technology will provide the capability to integrate active controls, flight controls, and a myriad of other capabilities to enable helicopters and rotorcraft to interface with users and perform missions in completely new ways. The result will be nothing less than quantum leaps in technology and a metamorphosis of rotorcraft into vehicles with unprecedented new capabilities.

This section of the paper provides an overview of these current revolutionary research thrusts. This section also provides a basis for the following section that looks toward a vision of vertical flight

concepts in 2025. It is useful to outline briefly the organizational elements of the Division and some of the major investment plans before undertaking this overview. The two technical branches comprising the Army/NASA Rotorcraft Division are the Flight Control and Cockpit Integration Branch and the Aeromechanics Branch.

The Flight Control and Cockpit Integration Branch is responsible for the development and insertion of advanced controls, guidance, and display technology for rotorcraft and powered-lift aircraft, and for the integration of these technologies to achieve safer and more effective pilot-vehicle performance. The research efforts include (1) definition of design and certification criteria, (2) investigation of operational problems including their human factors elements, (3) development of display and advanced control concepts for both piloted and remotely-piloted rotorcraft, and (4) development of automation, guidance, navigation, and displays for rotorcraft operating in all-weather, near-terrain conditions. In researching and demonstrating these technologies, the branch employs an array of analytical, simulation, and flight research tools.

The Aeromechanics Branch is responsible for aeromechanics research activities that directly support the Department of Defense and the U.S. rotorcraft industry. Branch programs address all aspects of rotorcraft that directly influence vehicle performance, structural and dynamic response, external acoustics, vibration, and aeroelastic stability. The programs are both theoretical and experimental in nature. Advanced computational methodology research using computational fluid dynamics and multidisciplinary comprehensive analyses seeks to improve the understanding of the complete rotorcraft operating environment and to develop analytical models to predict rotorcraft aerodynamic, aeroacoustic, aeroelastic, and dynamic behavior. Experimental research seeks to obtain accurate data to validate these analyses, investigate phenomena currently beyond predictive capability, and to achieve rapid solutions to flight vehicle problems. Databases from the flight and wind tunnel experimental programs are validated, documented and maintained for the benefit of the U.S. rotorcraft technology base.

Substantial investments and future plans are currently in place to develop and validate the key technologies for helicopters, tiltrotor aircraft, and other advanced rotary-wing concepts. New sophisticated research test stands and facilities have

been, or are being, developed. Among these new research facilities are the Tilt Rotor Aeroacoustic Model (TRAM) and the Large Rotor Test Apparatus (LRTA), Ref. 6. The Army/NASA Rotorcraft Division continues to rely on, and strongly support, the NASA National Full-scale Aerodynamics Complex, the Vertical Motion Simulator, and the Army Flight Project Office at Ames Research Center. The Division plays a major advisory, and participatory, role in National Rotorcraft Technology Center (Ref. 7) projects and continues to make significant contributions to the NASA Aviation System Capacity Program's Short Haul (Civil Tiltrotor) project (Ref. 8).

The following discussion outlines some of the revolutionary research opportunities in advanced rotorcraft technology being pursued within the Army/NASA Rotorcraft Division.

#### High Lift Airfoils and the Stall Free Rotor

Unlike fixed wing aircraft, helicopter rotors have traditionally relied upon relatively simple airfoils because of the conflicting aerodynamic requirements, aeroelastic constraints, and the need for structural simplicity and operational reliability. As a consequence the significant performance benefits of high-lift airfoils that are taken for granted by fixed-wing aircraft designers have not been exploited for rotorcraft. In view of the potential benefits, there is increasing interest in developing variable geometry airfoils and aerodynamic flow control technologies for rotorcraft. If sufficiently successful, such airfoils may enable a reduction in rotor solidity with a consequent increase of rotor efficiency and/or enable an increase in the high-speed maneuver margin of the helicopter.

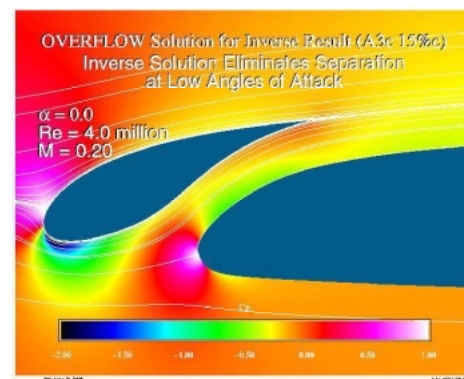


Fig. 1 - High-lift airfoil design using OVERFLOW CFD code.

There are several opportunities and potential approaches. Recent studies (Ref. 9) have begun to explore the application of advanced airfoil design methodology including Navier-Stokes CFD codes to design of multi-element airfoils with leading edge slots, Fig. 1. The unique rotorcraft challenge is to achieve the high lift of a slotted airfoil to delay stall on the helicopter rotor retreating blade without incurring a significant drag penalty at the low angles of attack of the advancing blade in high-speed forward flight.

Another high-lift airfoil approach is to introduce a variable geometry, such as a deployable leading edge slat or variable leading edge contour. Variable leading edge camber or droop would be especially beneficial since no drag penalty would be incurred for azimuthal locations operating at low lift, although such concepts pose demanding actuator and structural requirements. Finally, new approaches to active flow control based on low-mass flow, oscillatory blowing concepts have emerged. So-called virtual jets energized by smart material actuators may be a possible implementation approach.

There are far reaching ramifications for this technology. If the stall angle of attack of rotor blade airfoils can be extended beyond the range of helicopter blade pitch angle control inputs, a revolutionary new concept will become a reality - the *Stall-Free Rotor*. The implications for rotorcraft, beyond the performance, blade loads, and vibration benefits, will be of great significance by removing retreating blade stall as a major flying qualities constraint and contribute to the achievement of helicopter carefree maneuvering.

#### The Jet Smooth Ride and Whisper Quiet Rotor

Smart structure active control rotor concepts based on a coalescence of smart materials, active controls, and information technology have the potential to revolutionize future rotorcraft by reducing vibration, acoustic signature, and improving mission performance. Decreasing vibration will produce a major increase in time-between-overhaul of aircraft critical components while reducing structural fatigue, boosting avionics and subsystems reliability, and bringing safer and longer service life for rotor blades, drive shafts, engines, transmissions, and airframes. A smoother ride will also reduce fatigue and improve aircrew effectiveness. Attacking the problem at the source by integrating on-blade control surfaces, smart structures, sensors, and microelectronics, into a sophisticated active

control system will open the door to multiple benefits for rotorcraft. Plans include wind-tunnel testing of Mach-scaled rotors with active on-blade controls and smart material actuators to explore advanced design configurations beyond exploratory small-scale model experiments (Ref. 10) depicted in Fig. 2.

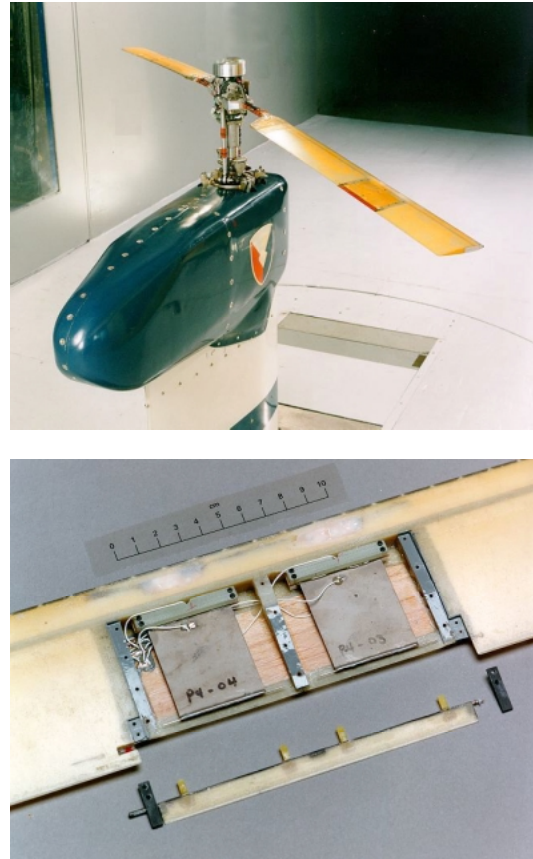


Fig. 2 - AFDD 7.5-ft experimental rotor with on-blade elevons and smart material piezo-ceramic actuator to reduce vibratory blade loads.

#### Individual Blade Control

The Division is also pursuing individual blade control (IBC) approaches in full-scale rotor tests. Under the Rotorcraft Algorithm Development and Integrated Control Laws (RADICL) program, the U.S. Army, Sikorsky, ZF Luftfahrttechnik, and NASA Ames Research Center seek to develop integrated control laws to suppress both noise and vibration without losing helicopter performance. The RADICL program approach will replace the UH-60 rotor blade pitch links with servo-actuators and perform tests in the Ames 40- by 80-Foot Wind Tunnel similar to the BO 105 rotor (Ref. 11). Promising controller algorithms will also be

simulated in the Ames Vertical Motion Simulator to determine the effect of IBC on handling qualities and flight dynamics. A potential flight test program will also be considered.

#### Tiltrotor Active Rotor Control

The Army/NASA Rotorcraft Division has also made substantial progress recently to demonstrate the potential of higher harmonic control (HHC) for tiltrotor rotor noise reduction. The most recent effort has been an 80-by-120 Foot Wind Tunnel test in the Ames National Full-scale Aerodynamics Complex (NFAC) with an XV-15 isolated tiltrotor, for both 3- and 4-blade rotors in low-speed, helicopter-mode flight, Fig. 3. This wind tunnel effort was conducted in support of the Short Haul Civil Tiltrotor program, which is an element of the NASA Aviation System Capacity program. Dramatic noise reduction results (both on- and off-peak BVI descent conditions) on the order of 7-12 dB were measured.



Fig. 3 - XV-15 Aeroacoustic Test

#### The Swashplateless Rotor

Smart structures and active control technologies also have the potential to change the fundamental design approach and configuration of the rotor hub, blades, and controls first originated with the invention of the helicopter in the late 1930s. Ultimately, active on-blade control concepts may eliminate the conventional controls such as the

swashplate, pitch links, and hydraulic flight control actuators, significantly reducing complexity of the helicopter and improving weight, maintenance and reliability. A notional concept including on-blade active control is depicted in Fig. 4.

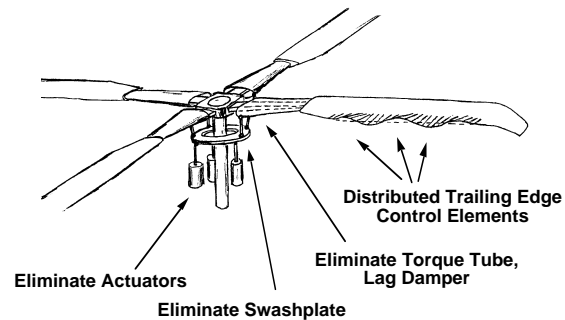


Fig. 4 - Swashplateless rotor concept with integral airfoil actuator.

#### Advanced Actuator Technologies

Active on-blade control and active fiber composites for integral twist rotor blades are advancing smart material structures and actuator technologies. Other smart material technologies are being pursued to integrate the actuation material into the airfoil structure to provide continuous airfoil trailing edge camber change as an alternative to discrete hinged control surfaces. Several innovative concepts in these areas are supported by Army and NASA SBIR funding. One of the actuator approaches being investigated is an electromagnetic actuator for on-blade controls depicted in Fig. 5 that has been whirl tested on a full-scale OH-58 rotor (Ref. 12).

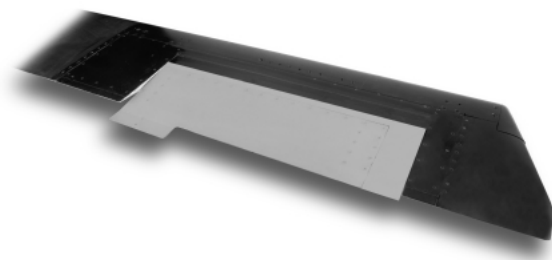


Fig. 5 - Heliflap™ electromagnetic actuator for on-blade control whirl tested on OH-58 rotor.

#### Active Control of Rotorcraft Aeroelastic Stability.

One of the major constraints on the design of many rotorcraft - especially for advanced configurations -



is the ever-present risk of aeroelastic, aeromechanical, or aeroservoelastic instabilities involving the rotor blade, flight control system, drive train, or rotor-body coupling. Inability to control these instabilities results in degraded mission performance, reduced payload, increased weight and cost and sometimes results in the addition of auxiliary dampers. In some cases, such instabilities render promising advanced rotorcraft designs unfeasible. Solutions involve automatic controls with new computer and sensor technologies to enable sufficient reliability, fail safety, and cost effectiveness to solve the problem. Other approaches involve more effective auxiliary damper materials, hybrid structural materials with damping material in composite blade structures and hybrid structures using passive or active smart materials. Expected achievements include damperless bearingless rotors, soft-inplane tiltrotors, 4- and 5-blade tiltrotors, and high-speed tiltrotor configurations with aerodynamically efficient wing sections.

#### Rotorcraft Design Methodology - Information Technology Revolution

Timely, low risk, cost effective design of modern rotorcraft and system upgrades requires accurate, robust, and reliable analytical prediction methods. Moreover, accurate design methods are essential to develop future advanced civil and military rotorcraft that maximize mission performance capability - limitations in design methodology result in sub-optimum designs and reduced mission performance.

The last twenty-five years have seen development of increasingly sophisticated and detailed analytical models of rotorcraft phenomena including major advances in CFD to model complex aerodynamic phenomena, sophisticated structural mechanics theory, and the development of comprehensive analysis codes that integrate aerodynamics, structural dynamics, propulsion, and flight control systems together in complete software packages. However, the prediction of essential aeromechanics design characteristics (performance, loads, vibration, stability, acoustics, and flight dynamics) does not yet satisfy the accuracy and reliability needs of rotorcraft designers. This results in inefficient designs, excessive testing and high risk, which greatly increase development costs.

There are a number of reasons for this situation. Accurate prediction of rotorcraft aeromechanics is inherently difficult. Rotorcraft encompass multiple disciplines and distinctly different phenomena and

computational approaches. Aerophysics are insufficiently understood to formulate accurate math models. One of the most critical, yet least understood is rotorcraft aerodynamics including stall, compressibility, flow separation, wakes, and vortices. Accuracy requirements are high - designers need not only first order effects, but higher order unsteady effects as well. Critical analyses involve limit conditions where stall and compressibility dominate. It will not be possible to adequately support the designer until accurate models for rotorcraft aeromechanics phenomena are achieved.

Many research efforts are underway including advanced CFD methods, hybrid aerodynamic approaches, multidisciplinary comprehensive analyses and experiments to acquire data to explore critical fundamental physical phenomena and validate design methodology codes. Two examples of this research will be briefly described.

Optimum Rotor Performance with Advanced Design Methodology. Development of optimum rotor configurations is exploiting efficient new aerodynamic design methodology based on hybrid computational fluid dynamic (CFD) codes incorporating vorticity embedding for computational efficiency.

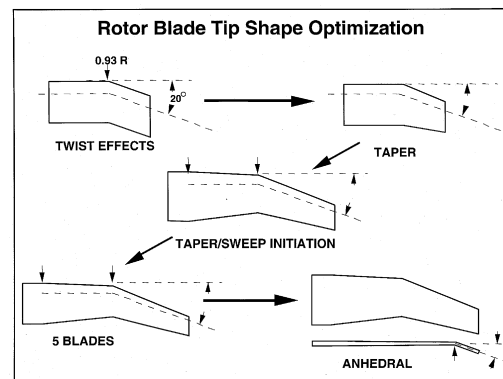


Fig. 6 - Advanced design methodology improves rotor hover performance.

Application of this analysis capability permits the practical optimization of subtle refinements in rotor blade tip shape, twist, taper, sweepback, and anhedral to reduce rotor power requirements, Fig. 6. Typical results for an Apache-sized helicopter indicate a 1000-lb increase in hover thrust for the same installed power.

Numerical Simulations of Rotors and Wakes on Parallel Computers. New approaches aim to accurately predict the rotary-wing vortex wakes, a problem that has plagued rotor designers for the past 70 years. The rotor wake problem is currently among the least understood and most important factor that drives rotorcraft design and performance and is the most challenging problem in rotorcraft CFD. Typically, numerical dissipation causes the computed vortical wakes diffuse too rapidly. New approaches will leverage the power of large-scale parallel computers and will employ several body-fitted structured grid systems attached to the moving rotor blades. These rotating grids move through overset Cartesian background grids that capture the rotor wake system. The flow solver will be an MPI-parallel version of NASA's OVERFLOW Navier-Stokes solver for which Meakin et al. (Ref. 13) have demonstrated good parallel performance for an unsteady simulation of the V-22 tilt rotor in high-speed cruise. This V-22 simulation used a total of 268 grid components and close to 28 million grid points. Particle traces from the rotor blades are shown in Fig. 7. Larger calculations will be undertaken (up to 100 million grid points), with the hope that the computed rotor performance results will show grid independence. Calculations will be used as a stepping stone towards running much larger problems on NASA's Information Power Grid. Ultimately, the goal is to dramatically improve the ability to model rotor wake systems.

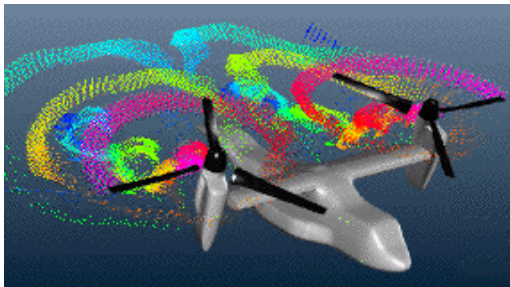


Fig. 7 - V-22 calculations point to advances in rotorcraft CFD predictions.

#### Aeromechanics Technology Impact

The synergistic impact of combining advanced rotor blade airfoils, active control, and swashplateless rotor technologies will be very large. Even for a constrained example, retrofitting such a rotor to a current utility helicopter would increase range and payload 86% and 55% respectively compared to the baseline vehicle. Figure 8 indicates the

contributions of each of the individual technical disciplines to the total increased range.

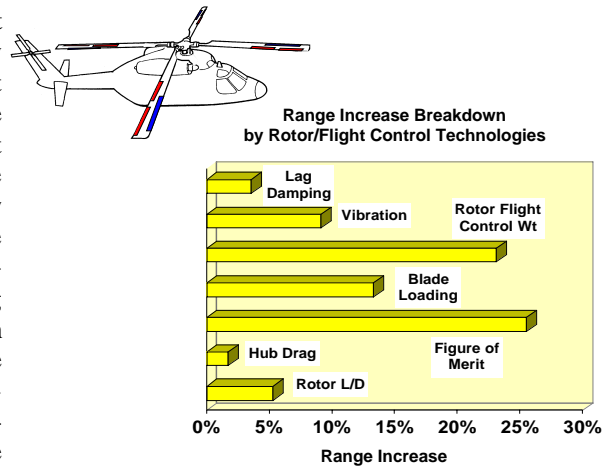


Fig. 8 - Impact of aeromechanics technologies for typical utility aircraft mission.

#### Helicopter Active Control Technology (HACT)

Future military rotorcraft will require major improvements in all-weather/night mission performance, maneuverability/agility, flight safety, and reduced accident rate. At the same time significant improvement in operation and support costs is needed, as well as reduced development time and cost. The Division is actively participating in the HACT program, a joint activity of the Aeroflightdynamics Directorate and the Aviation Applied Technology Directorate. The HACT program will demonstrate integrated, state-of-the-art rotorcraft flight control technologies with exploitation of advanced fixed-wing hardware components and architectures. The objective is to demonstrate, through simulation and flight test, second-generation rotorcraft digital fly-by-wire/light-control systems with fault-tolerant architectures, including carefree maneuvering; task-compliant control law; and integrated fire, fuel, and flight control capabilities. There are major technical barriers such as the lack of knowledge of optimal rotorcraft response types; inadequate techniques for sensing envelope limits, cueing the pilot, or limiting pilot inputs; inadequate air vehicle math modeling for high-bandwidth flight control; inadequate flight control system design, optimization, and validation techniques; and lack of knowledge as to the optimum functional integration of flight control, weapon systems, and pilot interface. These challenges will be met by implementing state-of-the-art rotary wing flight control technologies in an

advanced flight demonstration rotorcraft, exploiting advanced fixed-wing flight control architectures and fly-by-light hardware, and optimizing control laws for all parts of the flight envelope. Envelope cueing and limiting techniques will be implemented will to achieve carefree maneuvering, Fig. 9. To help optimize the design process as well as improve the product, it will be necessary to use advanced math models and rotorcraft flight control design techniques for analysis and simulation.

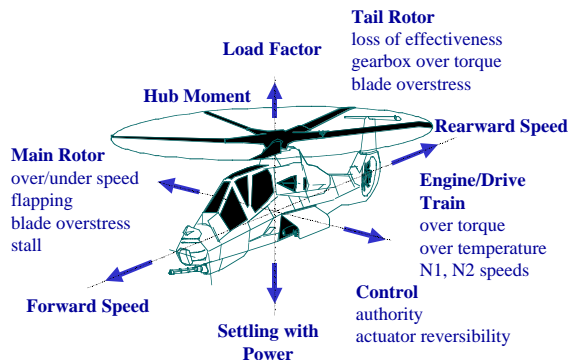


Fig. 9 - Multiple Limiting Factors and Flight Conditions Impact Rotorcraft Carefree Maneuvering

#### Flight Control Design Cycle Technologies

Unique capabilities and expertise within the Ames Research Center Flight Control and Cockpit Integration (ARH) branch are playing a critical role in aircraft design cycle reduction based on development and widespread application of the CONDUIT, RIPTIDE, and CIFER<sup>®</sup> tools.

The Control-System Designer's Unified Interface (CONDUIT) provides an environment for design, integration, and data resource management for the aircraft flight control system designer (Fig. 10). It is a sophisticated "associate" that provides comprehensive analysis support and design guidance to a knowledgeable designer. Flight control system design involves application of comprehensive specifications and sophisticated time and frequency-domain evaluation techniques to ensure desired performance and handling-qualities of highly-augmented modern combat aircraft and to minimize flight test tuning. Thus, the costs to continually retune control laws and handling-qualities predictions as updates in math models and hardware test data become available are prohibitive. CONDUIT drastically reduces the time and effort required for this process. The capabilities of the CONDUIT system have been evaluated through a

series of design problems based on the RASCAL, UH-60, and X-29 aircraft flight control systems and have been widely used by the rotorcraft industry.

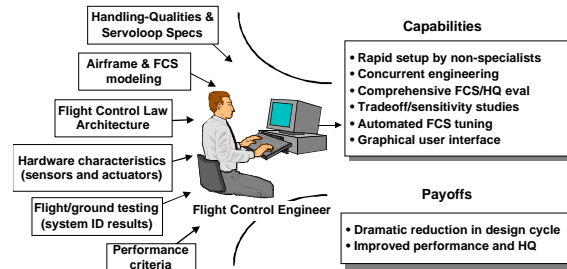


Fig. 10 - CONDUIT, Control Designer's Unified Interface, an environment for design, integration, and data resource management.

RIPTIDE is a software simulation environment for Real time Interactive Prototype Technology Integration Development Environment. Piloted simulation evaluation of a notional control law design using a high-fidelity non-linear mathematical model has always involved a complex and lengthy integration process because math models and control law design tools are not typically designed to work together. As a result, the integration process has not lent itself to rapid prototyping, whereby ideas can be quickly implemented and tested without significantly lengthening the development cycle.

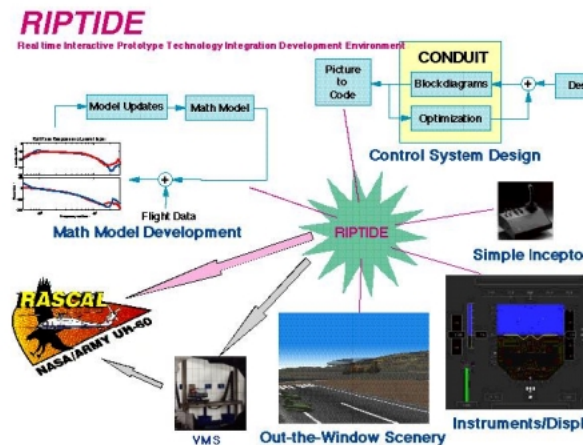


Fig. 11 - RIPTIDE allows concurrent research in various disciplines.



RIPTIDE eliminates this lengthy integration process. This is accomplished by treating each component of the simulation as an independent process and providing inter-process communication through shared computer memory. Also, process timing and scheduling ensures that the various components of the simulation are executed in the proper order. RIPTIDE is a perfect complement to CONDUIT and can also be used to concurrently conduct mathematical model development, control system design, and cockpit-display-concepts evaluation (Fig. 11). The environment makes piloted simulation readily available and each discipline is able to take advantage of tools developed by the other disciplines.

CIFER<sup>®</sup> is an integrated facility for system identification based on a comprehensive frequency-response approach jointly developed by the U.S. Army/NASA and Raytheon, STX. System identification is a procedure by which a mathematical description of vehicle or component dynamic behavior is extracted from test data and CIFER performs this function, without requiring a time-consuming modeling effort. Applications of system identification results include validation and update of simulation models, handling-qualities analyses and specification compliance, and optimization of automatic flight control systems. The foundation of the approach is the high-quality extraction of a complete multi-input/multi-output (MIMO) set of non-parametric input-to-output frequency responses. These responses fully characterize the coupled characteristics of the system. Army and NASA researchers have successfully used this capability in numerous rotorcraft flight test programs, including: Comanche, OH-58, AH-64, SH-2G, KMAX, A300, B214ST, B206, BO105, UH60, and most recently the Northrop-Grumman VTUAV.

#### Advanced Technology Rotor Demonstrators

The Joint Transport Rotorcraft (JTR) is envisioned to be DOD's future cargo logistics transport VTOL air vehicle, e.g., helicopter, tilt rotor, or other advanced configuration. Two pre-cursor programs are currently in progress or being defined to validate technology for this new generation of advanced rotorcraft: the Variable Geometry Advanced Rotorcraft Technology (VGART) and the Variable Geometry Advanced Rotorcraft Demonstrator (VGARD) programs. The VGART program is currently underway with both Army and industry technology development efforts. It involves development and testing of advanced rotorcraft

technology concepts with the intent to advance critical sub-component technology for future development of the JTR demonstrator aircraft. The key elements involve critical rotor component evaluation and testing for reliability, affordability, and scalability of advanced technology, including variable geometry concepts. The VGARD program will lead to a full-scale wind tunnel or flight demonstration of VGART developments. The Army/NASA Rotorcraft Division is fully supporting VGART and VGARD.

#### Biomimetics Initiative

NASA sees considerable promise across the whole of the agency for the application of a new design paradigm for aerospace systems. *Biomimetics - to mimic life, to imitate biological systems, technology inspired by biology.* The concept of biology-inspired technical solutions may have application in a wide variety of areas including cross-platform technology transfer to the rotorcraft community. Although, this is a relatively new initiative, the Division has begun to investigate potentially relevant topic areas and some of these include: 1) development of micro-air vehicles, 2) bio-inspired analogues for control such as sensing, stabilization, and navigation, 3) reconfigurable or variable geometry rotorcraft embracing adaptable smart skins and artificial muscle concepts for control surface actuation, 4) multiple vehicle coordination and mission execution (swarms or teams, multiple players), and 5) health monitoring, control, and sensors.

#### Applications of Rotorcraft Technology in Extraterrestrial Environments

The Army/NASA Rotorcraft Division has begun to perform and sponsor conceptual design studies of vertical lift planetary aerial vehicles -- with emphasis on Martian autonomous rotorcraft concepts (Fig. 12). Reference 14 identified that there are three planetary bodies (other than Earth) in our solar system where vertical lift vehicles for planetary science/exploration might be feasible: Mars, Venus, and Titan (a moon of Saturn). Further, reference 14 also emphasized that planetary science missions to the outer, gas-giant planets -- where vertical lift capability is not required as these planets do not have surfaces to interact with in a conventional sense -- could still benefit from the development of planetary aerial vehicles that employ rotary-wing-related technologies, such as propeller design. The extreme range of planetary

atmospheric characteristics will dictate substantial innovation in future rotary-wing technologies and vehicle design. Vehicle autonomy, in particular, is a critical enabling technology for vertical lift planetary aerial vehicles because of mission distances and the communication time lag between the vehicle and mission control on Earth.

Besides the reference 14 study, other work on vertical lift planetary aerial vehicles is currently underway within the Army/NASA Rotorcraft Division. A small number of university grants have been, or soon will be, initiated to study autonomous systems technology for vertical lift planetary aerial vehicles. Conceptual design work is in process developing proof-of-concept ground test hardware for the in-house Martian autonomous rotorcraft effort. Finally, the year 2000 AHS Student Design Competition is currently underway and is focused on the design topic of a Martian autonomous rotorcraft.

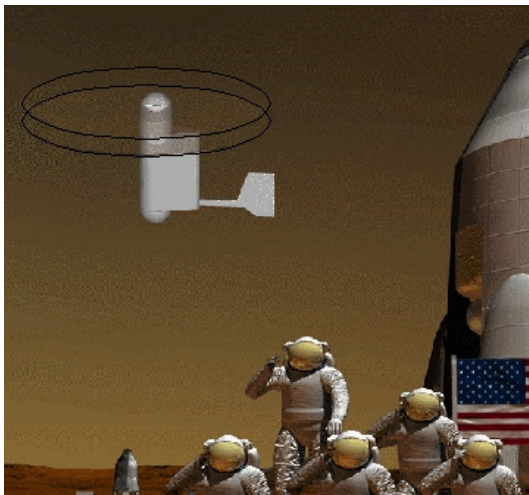


Fig. 12 - Vertical Lift Planetary Aerial Vehicles

#### Future Vertical Flight Vehicle Development and Demonstration

NASA, as part of its Flight Research R&T Base Program, has initiated in program year 2000 the Revolutionary Concepts (REVCON) project. This project is intended to foster revolutionary technology leaps in aeronautics through an expedited vehicle concept development cycle that quickly (three to five years nominally) leads to flight test demonstrations of the targeted technologies. A key feature of the REVCON project is the encouragement of substantive teaming partnerships of industry, NASA/US Government

agencies, and academia in planning and executing the proposed efforts. Because of the short development cycle dictated by the REVCON project requirements, uninhabited aerial vehicles for the flight test demonstrations are included in many of the proposals submitted to the project. These vehicles demonstrate varying levels of flight autonomy. Many innovative rotary-wing concepts, to date, have been proposed for the NASA REVCON project. The large number and variety of rotorcraft proposals to the REVCON project send a clear message that innovation is alive and well in the rotorcraft community.

Although the technology being developed under these advanced Army and NASA research thrusts is truly revolutionary, there is a continuing need to envision the world of the future to ensure that the rotorcraft technology plan is appropriately focused. This requirement for a fresh look at the future led to the development of "Vertical Flight 2025".

### **"Vertical Flight 2025": A Strategic Vision for Revolutionary Flight Concepts**

In June 1999, members of the Ames rotorcraft community gathered to brainstorm ideas for the future of Vertical Flight in the year 2025. Dr. L.S. "Skip" Fletcher, Ames Director of Aerospace, participated in this symposium and challenged all the participants to visualize the world in 2025 and to determine what new missions and markets could be opened by rotorcraft and other vehicles capable of vertical flight. Fletcher then asked that the members of this Rotorcraft "think tank" begin to define the technology barriers which would have to be overcome in order to realize this vision of "Vertical Flight 2025" and the research programs necessary to resolve them.

The outcome of this process was the recognition that there will be significant market potential for two very different classes of vertical flight vehicles: ultra-small-scale vehicles operating autonomously and larger-scale, "user-friendly" vehicles capable of carrying a significant payload.

#### Roto-Mobile

A potentially huge niche market for an application of rotorcraft technologies is the personal

transportation system: single- or multiple-passenger vehicles with the ability to takeoff and land vertically and to be operated either autonomously or manually with “car-like” controls. Significant military advantages could be realized with such vehicles, including rapid mobility with minimum casualties by bypassing obstacles such as land mines, blocked roads, impassable bridges, and large bodies of water; rapid-response search and rescue, reconnaissance, and surveillance; and insertion of Special Forces. These “Roto-Mobiles” could also be used to:

- offload highway systems to improve the capacity of ground transportation systems,
- allow rapid, door-to-door transportation to and from airports,
- provide instant-response medical attention,
- yield an order-of-magnitude decrease in package delivery time,
- provide transportation for our growing communities of senior citizens,
- provide a third dimension for the Sport Utility Vehicle

Higher Capacity Utility Roto-Mobiles could be developed and marketed to:

- assist in the construction and maintenance of power lines, bridges, and multi-story buildings
- replace ground vehicles for agricultural tasks such as planting, spraying, and harvesting;
- make significant improvements in the productivity of aquaculture;
- provide a stationary airborne communications facility or large radar platform;
- participate in major chemical and biological cleanups;
- detect and extract land mines; and
- conduct search and rescue operations in adverse weather conditions

Although many attempts have been made in the past to tap this market by developing both civil and military personal transportation systems, significant technical barriers have caused these efforts to be less than successful. With its expertise in rotorcraft aeromechanics and control, human factors, and air traffic management, Ames is particularly well-qualified to participate in the advanced technology development required for a successful Roto-Mobile.

#### Small Autonomous Rotorcraft & Micro-Rotorcraft

The "Vision 2025" exercise confirmed the tremendous potential of developing small autonomous rotorcraft and their associated enabling technologies. Small Autonomous Rotorcraft is envisioned as a class of vehicles which range in grams of gross weight for “Micro-Rotorcraft” to thousands of kilograms for conventional-sized rotorcraft uninhabited aerial vehicles). Small autonomous rotorcraft represents, therefore, a broad spectrum of vehicles that will have unique applications, missions, and market potential depending, in part, on their size and payload capacity.

In particular, the potential applications for the smallest of small autonomous rotorcraft -- or Micro-Rotorcraft -- are enormous in number. These include operations alone or in collaborative teams for:

- atmospheric sensing such as wind shear detection and meteorological measurements;
- stealthy urban warfare surveillance;
- public service applications such as immigration, drug enforcement, and public safety;
- operations in contaminated environments unsuitable for humans, and
- planetary exploration as “astronaut agents”.

Already prototype vehicles are being developed in the two size extremes of small autonomous rotorcraft: rotary-wing micro air vehicles being developed in response to DARPA sponsorship and rotorcraft UAVs being developed under Industry and U.S. Navy and Marine sponsorship. Nonetheless, opportunities also exist for vehicles that fall in the intermediate ranges of size and payload capacity.

The common integral feature of small autonomous rotorcraft is the emerging field of 'intelligent systems' and autonomous vehicle control. Just as advances in more traditional rotorcraft technologies -- such as composite materials and turbine engine propulsion -- have radically changed the nature of rotorcraft over the past thirty years, autonomous system technology will have a corresponding transformative effect. Finally, because of the very small scale of some of the small autonomous rotorcraft ("micro-rotorcraft"), there will be unique technical challenges for these vehicles in the area of

materials and structures, propulsion, aerodynamics, control of flight, and ground and flight testing.

As lead Center for Information Technology and Rotorcraft, Ames is well-positioned for its role in the development of the high-payoff technologies implicit in the development of small autonomous rotorcraft.

#### Challenges for Implementing the Vision

Implementation of the “Vertical Flight 2025” vision is as critical as, if not more so than, developing the vision itself. As with the results of any creative thinking, there are always obstacles to be dealt with before reaping the potential benefits. To overcome the technical and socioeconomic barriers implicit in the development of rotorcraft personal transportation systems (“roto-mobiles”) and small autonomous rotorcraft, carefully selected and planned research projects must be initiated and executed. Given the current limitations in both financial and human resources available to the Ames rotorcraft community, it is important to make reasoned decisions about the initiation of new, bold research projects such as the ones identified in the “Vertical Flight 2025” process. Our current commitments, both to existing NASA and U.S. Army research programs, must continue to be the primary focus of our research portfolio.

Therefore, in addition to being creative in establishing a vision, creativity is also required in its implementation. Government researchers must be prepared to operate in ways that might be very unfamiliar, and even uncomfortable, to them. Small, focused, highly-competent teams made up of members from many different scientific and engineering disciplines, working across organizational boundaries, will be required to perform in a “Skunk Works” fashion. New, efficient ways of working with small, creative private sector companies must be invented. Universities must participate as equal partners. In these lean budget times, “creative financing” must be employed. New budget sources for “venture capital” must be identified. Short-term projects that address problems that can actually be solved must be included in the research portfolio. Affordable projects that convincingly demonstrate the attributes of these new vehicle concepts, such as a new operational capability, safe operations, and reliable automation, must be designed and carried out. But, above all, it is important for these research teams to:

- *Do fabulous work and be known around the world for (their) innovativeness.*
- *Attract exciting people -- more than a few of whom are a little offbeat.*
- *Raise hell, constantly question "the way things are done around here," and never, ever rest on (their) laurels. (Today's laurels are tomorrow's compost.)*

**Tom Peters (author of “In Search of Excellence”)**

The following sections of the paper provide additional details on the design and technology opportunities and challenges implicit in the development of rotorcraft personal transportation systems and small autonomous rotorcraft, as well as provide a report on the efforts made to date to realize the vision of “Vertical Flight 2025”.

### **Vision 2025: The “Roto-Mobile” – A Personal Transportation System**

#### Introductory Remarks

The concept of a simple flight vehicle for personal transportation has been an enduring dream for many years, Fig. 13. To be truly revolutionary, such a vehicle must be compact, economical, safe, easy to operate, environmentally friendly, and particularly significant, runway independent. Aside from the ability to takeoff and land vertically, this implies capabilities heretofore unattainable in a flight vehicle. However, with today's rapidly advancing technology, such a vehicle may well be achievable. For example, consistent with the Division's Vertical Flight 2025 strategic vision effort described earlier, the concept of revolutionary flight vehicles that can significantly improve the short haul and commuter

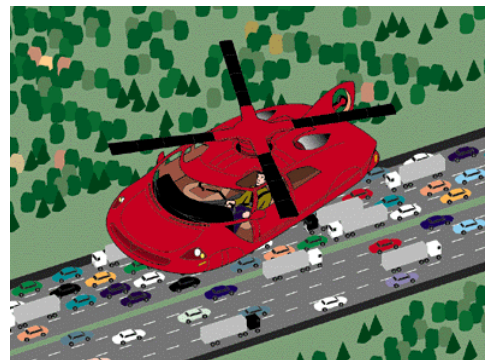


Fig. 13 –Rotorcraft Personal Transportation System Concept

transportation capacity (throughput) of the country is gaining increasing acceptance by aerospace leaders (Ref. 4).

The Small Aircraft Transportation System (SATS) concept being led by NASA/FAA/DOT seeks to advance transportation infrastructure and vehicle technologies to satisfy a significant portion of the 21st century transportation demand of the nation and relieve pressure on existing ground and air systems (Ref. 15). In recent years, noted aerospace technologists have recognized growing technological capability converging with the vision specifically for vertical flight vehicles (Refs. 16 and 17). The concept Roto-Mobile class of vertical flight vehicle is intended to represent a means for studying, advancing, and applying technologies potentially capable of realizing such a personal transportation vehicle.

Previous attempts to develop revolutionary personal aircraft comprise a variety of vehicles - the roadable airplane or flying car, individual lift devices or small flying platforms, and numerous small helicopters and VTOL aircraft concepts (Ref. 18). None of these devices has yet come close to achieving the dream of a personal transportation system. However, valuable experience has been gained toward the realization of the Roto-Mobile concept. This experience will be used as a basis to define a representative configuration and to identify the technical issues needing priority attention. Currently, the Roto-Mobile is envisioned with ducted fan(s) for lift and propulsion in view of general appeal, aerodynamic efficiency, and moderate downwash and noise. A rotor may require less power, but a compact, enclosed thruster will be safer, more compatible in confined spaces, and enjoy broader user acceptance.

To be more specific about the requirements, the Roto-Mobile is conceived as a revolutionary single- or multi-passenger vehicle able to 1) take off and land vertically from confined spaces and 2) operate semi-autonomously or with simple "car-like" controls. Such a vehicle must have unprecedented reliability and fail-safety and this will require simplicity, excellence in design, and the utmost in technology innovation. To be affordable, both in terms of acquisition and operating cost, it must be aerodynamically efficient, designed for ease of manufacture, and successful enough to gain cost savings from mass production. And finally, it must be practical, convenient, and easy to use in ways far beyond present day experience such as semi-autonomous or semi-automatic operation, providing

operators with personally adaptive controls and displays to navigate from designated landing and parking areas through controlled 3-D pathways in the sky.

The implied premise behind such a revolutionary concept is that recent and anticipated technological advances in a variety of disciplines may be combined with earlier concepts to overcome previous limitations and deficiencies. These new technologies include advanced computers, information technology, flight control systems, avionics and sensors, powerplants, and structural materials. Revolution in these disciplines will not automatically generate a revolutionary flight vehicle but will provide new opportunities for creative thinking, inventiveness, and enterprise to realize such a vehicle. The result will be nothing less than a reshaping of the way aviation impacts our way of life for transportation, recreation, and defense.

In this section of the paper, we consider some of the opportunities and discuss issues that must be addressed to make the Roto-Mobile concept a reality. We will also briefly describe technical activities underway at Ames Research Center to address technology needs as well as cooperative activities aimed at furthering this technology.

Schroeder's recent historical overview (Ref. 19) provides an up-to-date survey of the broad spectrum of individual flying platforms, including brief descriptions of approximately 30 different vertical takeoff and landing aircraft that have undergone some degree of flight testing. This survey outlines the prevalent approaches along with their advantages and disadvantages. The manifold problems illuminated a variety of technical issues that must be resolved before the Roto-Mobile concept can succeed.

Zimmerman (Ref. 20) developed the flying platform concept at NACA after hypothesizing that natural kinesthetic balancing reactions of a standing operator would stabilize a thrust device attached beneath his feet. A flurry of interest occurred during the 1950s when military interest generated support for a variety of experimental developments. Many of these configurations were conventional low-disc-loading rotors, but other types included ducted fan platforms, jet platforms, and even hydrogen peroxide rocket belts. The rotor platforms had the highest hovering efficiency but were less compact and compatible with confined area operation than ducted fans. Jet and rocket devices with poor propulsive efficiency suffered from



limited endurance and generated very high noise levels. Although there were some areas of success, the group of vehicles as a whole experienced significant technical obstacles that were largely unsolved. The main problems included marginal stability, lack of adequate control and handling qualities, and gust response sensitivity. Other problems included limited maneuver capability, pilot induced oscillations, and very low trimmed flight speed. Of course only limited stability and control augmentation systems were incorporated in these vehicles so lack of success is not surprising. Given adequate aerodynamic control power and modern flight control system technology, acceptable flying qualities should be achievable.

### Technical Challenges

A number of critical technical challenges that must be faced in several key technical discipline areas will be briefly discussed, including the potential of today's technologies and some suggestions on possible conceptual approaches.

Flight Control and Handling Qualities. Perhaps the single most important requirement for the Roto-Mobile concept is providing ease of control for the operator - and in ways that go far beyond the traditional meaning of handling qualities. A minimum requirement for a traditional flight vehicle would be satisfactory controllability by a skilled pilot and with proper application of modern flight control technology this capability should be available. However, to be a revolutionary vehicle, the Roto-Mobile should be flyable by another class of operator, requiring skills no more difficult to learn than those needed to drive a car. This will present challenges on several levels. It will be necessary to understand what this means in terms of vehicle requirements, and moreover, what "car-like" means when applied to a vehicle that operates in three dimensions. At one extreme it could mean fully automatic control with the operator merely selecting a destination and turning over full control and navigation to the vehicle. However, this is probably not desirable. To develop a sense of confidence in the vehicle, achieved through mastering control of the device, the operator will likely desire some degree of control over both maneuver and navigation. The key will be to determine the automatic flight control requirements needed to engender this sense of confidence. The appropriate degree of maneuvering control, ease of use, and navigability may vary according to the flight regime and piloting task. At the least, such

capabilities must be highly intuitive and not require the operator to undergo lengthy training to become a highly skilled "pilot." This requirement will place new demands on understanding flying qualities requirements and configuring control system architectures. One conceptual framework for the desired control functionality has already been proposed by Drees (Ref. 16).

Human Factors. Closely associated with the need to develop the appropriate flight control characteristics will be the need to examine human factors requirements; that is, the unique ergonomics and displays required for a VTOL aircraft that must operate safely. The human factors issues for the Roto-Mobile operator will present significant challenges.

Air System Operation. Requirements for both safety and the goal of helping to meet national transportation needs will require the Roto-Mobile to have revolutionary airspace operability. In this sense, the challenges for the Roto-Mobile concept go beyond the scope of issues addressed by earlier individual flying platform development projects - the significant fact is that the concept of a revolutionary vehicle cannot be viable unless the "infrastructure interface" requirements are satisfied. That is, a VTOL aircraft must operate safely and navigate within a controlled airspace environment. Navigation may be greatly facilitated by new technologies such as GPS systems. A successful vehicle will proliferate in large numbers and will require new approaches to air traffic control, separation, and collision avoidance, well beyond the challenges facing the current aircraft population. A number of these issues are being addressed in the context of the SATS program (Ref. 15) to advance the National Airspace System infrastructure including "Smart" airports, EnRoute and Terminal Free Flight, and satellite-based communications, navigation, and surveillance. For military applications, numerous navigation and control issues will need to be addressed to insure mission effectiveness and reduced vulnerability.

Safety and Reliability Characteristics. A revolution in flight vehicles will require an unprecedented level of intrinsic vehicle safety and reliability, in addition to safe operation of the vehicle airspace system. Vehicle safety and reliability involve the airframe structure, propulsion, flight control effectiveness, and reliability of electronics including avionics, sensors, and computers. Backup safety recovery systems need to be considered. Advanced technology offers many benefits for safety. Gas

turbine powerplants offer high reliability although few candidates are currently available for personal transportation-sized vehicles. Internal combustion engines are not normally considered highly reliable, however they can be made extremely reliable if designed accordingly. For example, multiple powerplant redundancy, derating to increase reliability and operating life, and multiple redundant electronic ignition and fuel injection systems will substantially increase reliability and safety. Advanced health and condition monitoring and fault detection systems will provide increased warning of impending failures. Structural reliability must be assured through intelligent design backed up by thorough qualification testing. Composite materials offer increased reliability, benign failure modes, and on-condition inspectability. Subsystem components such as actuators, flight control hardware, fuel systems, can be improved with design excellence, redundancy, derating, and thorough qualification testing. In the event a failure occurs, ballistic parachute recovery devices are available for light aircraft and other concepts may be developed that may ultimately offer backup safety devices effective throughout the entire flight envelope.

Flight Performance Efficiency. Flight performance will benefit significantly from improvements in aerodynamics, structures, propulsion, and flight control systems. For the reasons noted above, the basic Roto-Mobile concept will likely embody ducted fans for lift and propulsion in hover and forward flight. Application of advanced aerodynamic analysis methods, including CFD, and appropriate wind tunnel and free flight testing will help insure optimum performance capabilities for multiple operating conditions. Sufficient aerodynamic control power will be essential to overcome extremely limited forward flight speed capability of the ducted fan stand-on platform. Additionally, reducing the drag of the cylindrical shroud of the simple ducted fan will be needed to enable reasonable forward speeds with a fixed duct. At the present time it is unclear whether the fan ducts should be tilted to achieve forward flight, or whether a vane system (louvers) should be used for thrust deflection. In view of the cascading effects of increasing complexity, the appropriate configuration types will need to be determined in relation to mission requirements. Current powerplant technology should be sufficient to enable reasonable performance, however tailoring powerplants to specific size and operational requirements of the Roto-Mobile concept would undoubtedly enhance performance considerably. Similarly, advanced composite structures offer significant benefits that

should be exploited to enhance viability of the concept.

Environmental Impacts. Duct downwash, engine and ducted fan noise, and engine pollution are important considerations for success of the concept. One benefit of the ducted fan is relatively low downwash provided the disk loading is kept reasonably low. Engine noise will require muffler systems and ducted fan propellers will need to operate at relatively low tip speeds to be acceptable. Finally, engine exhaust pollution, especially for two-cycle reciprocating engines will have to be addressed particularly if such vehicles do indeed progress to the mass market.

#### Ames Activities

In view of the timeliness of the technology opportunities and the potential mission applications, the Army/NASA Rotorcraft Division has initiated several technical activities to study the Roto-Mobile concept and strengthen the technical base in preparation for possible future activities. These will be briefly described below.

NASA Ames Research center has entered into a Non-Reimbursable Space Act Agreement with Millennium Jet, Inc. to "assess the validity and feasibility of a personal rotorcraft for potential aircraft development to meet future national requirements to increase use of rotary wing aircraft and reduce the cost of air travel." Millennium Jet, Inc. (MJI) has designed, fabricated, and has initiated ground testing of a prototype individual flight vehicle called the SoloTrek™ XFV™ Exo-Skeleton Flying Vehicle.

The SoloTrek™ VTOL configuration (Ref. 21) is designed to transport a single operator in the standing position with a pair of fixed-pitch ducted fans mounted above the operator's shoulders and driven by a two-cycle, four-cylinder engine (Fig. 14). Under the terms of the agreement, MJI will provide engineering design analyses and conceptual designs and results of MJI analyses and tests while NASA will contribute government requirements, engineering and mission assessments, and results of selected NASA analyses and tests. MJI and NASA will jointly assess the adequacy of various designs and testing processes.

The Division is also initiating research involving small-scale wind tunnel testing of ducted fans to extend the experimental database for axial and oblique operating conditions and to study details of



Fig. 14 - SoloTrek™ XfV™ Exo-Skeleton Flying Vehicle.

duct flow separation and aerodynamic efficiency for variations in duct and fan design characteristics. Most importantly, this information will be used to compare with and refine aerodynamic analysis methods, including computational fluid dynamics (CFD) for ducted fan configurations. In the area of flight control and stability, preliminary simplified models will be employed to study the handling qualities and control system requirements of the Roto-Mobile concept and attempt to find ways of overcoming the problems that have plagued such concepts in the past.

## Vision 2025: Small Autonomous Rotorcraft

### Introductory Remarks

In addition to the vision of rotary-wing vehicles as being key components in a Personal Transport System, the other major strategic vision for rotorcraft as identified by senior technologists within the Army/NASA Rotorcraft Division is the development and use of small autonomous rotorcraft. Small autonomous rotorcraft are defined for the purposes of this paper to be a class of vehicles that ranges in size from very small rotary-wing micro air vehicles that weigh only a few grams

-- referred herein this paper as "micro-rotorcraft" (Fig. 15) -- to larger, more conventional, rotorcraft uninhabited aerial vehicles (UAVs) that have gross weights in the thousands of kilograms.

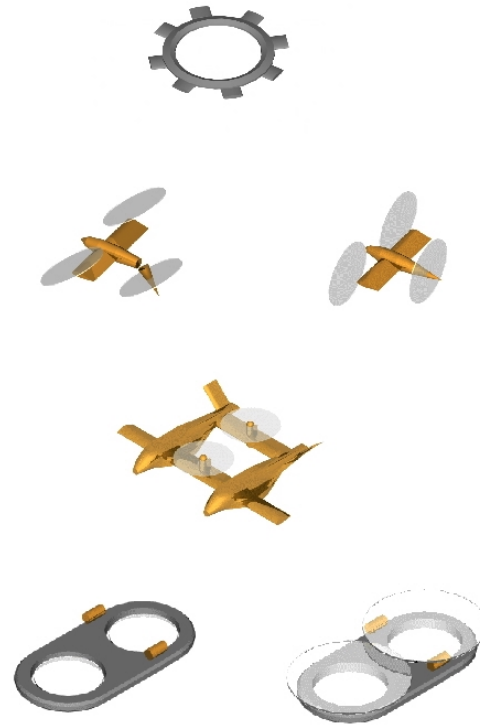


Fig. 15 -- Various Notional Micro-Rotorcraft Concepts.

What is the underlying rationale for the development of small autonomous rotorcraft? First and foremost, the "intelligent systems" capability inherent in small autonomous rotorcraft reduces or eliminates the human element in execution of these vehicles missions/applications -- thus significantly reducing operator cost and personal risk.

In a general sense, small autonomous rotorcraft can be seen to hold great promise in three primary areas: covert surveillance applications; mobile user interaction and utility functions; and implementation of rapid deployment of 'distributed' processes. Vehicle sizes and payload capacity for small autonomous rotorcraft is dependent upon the specific missions/applications being considered. This will be discussed in further detail.

Covert Surveillance. Covert surveillance applications could benefit from the inherent low observability of small autonomous rotorcraft -- particularly micro-rotorcraft. "Distributed"

missions/applications could call for the use of collaborative teams of vehicles, while doing so in a cost-effective manner. The mobility of small autonomous rotorcraft could enhance the flexibility of intelligence gathering versus remote, or nonmobile, sensors. Use of multiple distributed vehicles would minimize the impact of individual vehicle detection/compromise to the overall covert operation. Small vehicles are potentially easier to insert into a target territory unobtrusively. For example, small vehicle size could enable manual transport/fielding (a micro-rotorcraft size vehicle could easily be carried by one or two soldiers/operators/operatives). Very small, lightweight, and robust vehicles could alternatively potentially be dispersed efficiently by specialized 'carrier' vehicles. Finally, on the larger end of the small autonomous rotorcraft spectrum, the vehicles could be self-deployable from a home base.

Mobile User Interaction and Utility Function. It is currently not unusual for people to carry one or more digital electronic devices for day-to-day personal, professional, or recreational use. The future promises an explosion of personal digital devices. Even wearable computers are seriously being studied. Use of small autonomous rotorcraft for personal interactive services are a natural logical extrapolation of this trend. Micro-rotorcraft, in particular, could operate in close proximity to and interact with a human being to provide unprecedented personal utility and function. "Distributed" processing/sensing across multiple vehicles could provide enhanced utility without increasing any individual device/vehicle's weight/size. Further, vehicle mobility would reduce, or eliminate, the manual burden of transporting this functionality (versus hand-carried or wearable devices). For example, small autonomous rotorcraft could be used as flying 'personal' video cameras for high-end consumers/world-travelers. Other examples include: improved Secret Service protection for high-level politicians/dignitaries; improved management of prisoner release programs; personal security; truly secure communication through actual physical transfer of information by means of micro-rotorcraft acting as 'couriers.' On the other size extreme of the small autonomous rotorcraft spectrum for 'mobile user' applications is the semi-autonomous flight control of rotorcraft personal transport systems ("rotor-mobiles").

Rapid Deployment of Distributed Processes. Large areas can be surveyed or secured more quickly and comprehensively with multiple small autonomous

rotorcraft carrying multiple types of sensors and/or 'active elements.' This task can be accomplished most effectively with small, low-cost vehicles that can be rapidly and easily dispersed from 'carrier' vehicles, and are considered ultimately to be expendable. Examples could include: chemical spill surveys and clean-ups (timed release of petrochemical-eating bacteria as one example); surveillance for treaty violations of weapons of mass destruction (chemical, biological, and nuclear); plant/building physical security; border security; planetary exploration; revealing, documenting, and perhaps preventing potential crimes against humanity (via rapid insertion of active, intrusive, pervasive, and visible intelligence assets primarily comprised of micro-rotorcraft). Inevitably trade-offs must be made between larger sizes of small autonomous rotorcraft for improved capacity to carry payloads, to survey greater areas, or to stay longer on station for observations, versus smaller vehicles that could be more easily dispersed in larger numbers.

Table 1 is an qualitative assessment of the spectrum of small autonomous rotorcraft sizes and weight classes applicable for specific mission/applications (consistent with the three general application areas noted above). Though there is plenty of room for reasoned argument for whether a particular vehicle size can perform a given mission, this table hopefully provides a good starting point for follow-on discussion.

Most of the original interest in fixed-wing and rotary-wing micro air vehicles is due to the advocacy and support of DARPA. Reference 22 summarizes that interest for anticipated future DoD missions. Through DARPA support, a number of micro air vehicle concepts have been taken to proof-of-concept flight demonstrations. DARPA has imposed a maximum vehicle size limit of 15 cm in their ongoing micro air vehicle studies. But it is not clear that, in the long run, that this design-by-dictate approach is best. There are at least two different perspectives in the development of rotary-wing micro air vehicles. One perspective, seems to be about pushing the frontiers of micro-machine technology rather than being mission/application driven. However, at this early stage of investigation, both technical approaches (technology- versus mission- or application-driven) should be pursued.

Though a number of rotary-wing micro air vehicle (Ref.s 23-24) and rotorcraft UAV (Ref.s 25-28) development efforts are currently underway within

Table 1 -- Vehicle Size versus Types of Mission (A Partial List)

Types of Missions	<0.1m (<0.1kg)	0.1 - 1m (0.1 - 10kg)	1-3m (10- 100kg)	3-10m (50- 1000kg)	Rotor Diameter r > 10m (Vehicle Mass > 1000kg)
<b>Covert Surveillance</b>					
- Intelligence or reconnaissance in Building/Structure Interiors	■				
- Insertion/action in sensitive open (outside) environment	■				
- Border/camp boundary protection (discovery or observation only moderately critical)		■			
- Medium Altitude Surveillance (discovery or observation not critical)			■		
<b>Mobile User Interaction and Utility Function</b>					
- Personal aerial camera	■				
- Professional Media Aerial Platform	■	■			
Personal or professional level security		■	■		
- Personalized courier service		■	■		
- Personal transport autonomous support for 'automobile-like' control				■	
<b>Rapid Deployment of Distributed Processes</b>					
- Urban police security	■	■	■	■	
- Hazardous material tracking and clean-up action	■	■	■	■	
- International tribunal surveillance and documentation		■	■	■	
- Border patrol	■	■	■	■	

industry and academia, the promise of this vehicles has not yet been realized and many opportunities remain to develop enabling technologies for this broad class of 'small autonomous rotorcraft.' A mission-oriented perspective to vehicle development for small autonomous rotorcraft will likely point to the need to focus on intermediate vehicle sizes in addition to rotary-wing micro air vehicles and conventional rotorcraft UAVs.

## Technical Challenges

It is important to ask what are the technical issues for small autonomous rotorcraft -- particularly for micro-rotorcraft.

Low Reynolds number aerodynamics and low aspect ratio lifting surfaces will present challenges to develop vehicles with acceptable performance characteristics. Further, there is little empirical information/insight into the design of very small vehicles. The closest analog to small autonomous rotorcraft are hobbyist, or radio-controlled, helicopters. But the anticipated missions or applications for small autonomous rotorcraft require vehicle performance and system capability well beyond 'hobbyist' or 'industrial' radio-controlled helicopters. Nonetheless, some lessons learned from the hobbyist world might be applicable to small autonomous rotorcraft development.

Another set of technical challenges involve providing adequate onboard resources to perform practical missions/application (including providing adequate fuel/power to fly reasonable ranges and endurance, adequate payload fraction for mission package for sensors and downlink telemetry, high-speed, multiprocessor flight/mission computer architectures compatible with both low- and high-levels of autonomy. Low-cost manufacturability will be essential to small autonomous rotorcraft (a large number of these vehicles will be required as compared to larger vehicles, and these vehicles will likely be considered 'disposable'). Minimum man-in-the-loop effort is also essential for operating and interrogating these very small (and potentially large numbers of) rotorcraft vehicles.

Finally, vehicle range and endurance, particularly for vehicles powered by electric propulsion, will be a major issue. Current state of the art motor and battery technology limits electric-powered hobbyist helicopters less than a half-hour of flight at best. Endurance limitations of individual micro-rotorcraft, for example, can be compensated for by using multiple platforms to accomplish a given mission -- such that a constant cycle of vehicles could either be 'recharging' themselves or performing the station keeping mission. As these vehicles are very small and low-cost, such a constant re-supply/mission sortie cycle should be viable for even simple missions. One possibility to expedite such a constant re-supply/mission sortie cycle strategy would entail having a 'perch' for a swarm of micro-rotorcraft which would incorporate



an induction-plate electrical charger. Another possibility is to have the vehicles drop to the ground and recharge via solar cells before returning to flight and the mission.

Powerful market and technological forces will help influence the successful development of small autonomous rotorcraft. The fast-paced world of consumer electronic/digital products is driving the development of new advanced battery and/or fuel-cell technologies, micro-mechanical sensors, high-speed, low-power, distributed micro-processors, and other miniature electronic components necessary for small autonomous rotorcraft. Finally, there has been a renaissance recently as to automated reasoning software development and robotics. NASA research into information technology and intelligent systems research has seen significant increases in the past few years. NASA has a long-term strategic goal to develop robotic systems ostensibly for space and planetary science missions but with potential broad application – including autonomous rotorcraft. Further, this NASA strategic goal includes studies into distributed robotic ‘colonies’ with multiple, and heterogeneous groups of, ‘agents’ (Ref.s 29-36). All of this work in automated reasoning, robotics, robotic colonies, and distributed processing will have significant implications for the successful introduction of small autonomous rotorcraft.

#### Ames Activities

The first tentative steps towards to making this vision of small autonomous rotorcraft a pervasive part of our technological society are already being taken by the Army/NASA Rotorcraft Division. The NASA Intelligent Systems (IS) program and the Rotorcraft Division have initiated a cooperative project studying autonomous rotorcraft technology. Further, an in-house effort to develop various innovative vehicle configurations for micro-rotorcraft is also underway. These initial efforts will hopefully lead to comprehensive research programs that will examine the broad spectrum of small autonomous rotorcraft and, therefore, enable the strategic vision outlined in this paper.

### **Concluding Remarks**

Imagine it's the year 2025. In the sky above are dozens of miniature robotic helicopters measuring

only two to three inches in size darting about as you stroll to your one-person "Roto-Mobile" to begin your daily commute to your downtown office.

Sound farfetched? The Army/NASA Rotorcraft Division doesn't necessarily think so. Senior Division management and technical staff recently engaged in an effort to forecast the future of rotorcraft and other vehicles with a vertical flight capability. During this brainstorming session, it became apparent that there will be significant market potential for two very different classes of vertical flight vehicles: ultra-small-scale vehicles operating autonomously and larger-scale, 'user-friendly' vehicles capable of carrying a significant payload. The Army/NASA Rotorcraft Division is taking steps to formalize and implement this strategic vision of rotorcraft technology for the future.

This paper also highlights other ongoing revolutionary research thrusts within the Army/NASA Rotorcraft Division at Ames Research Center. This summary of revolutionary projects is not a comprehensive list but gives a broad perspective of the active and innovative research being conducted by the Army/NASA Rotorcraft Division.

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